

Cutoff in the Lyman α forest power spectrum: warm IGM or warm dark matter?

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We re-analyse high redshift and high resolution Lyman- α forest spectra from Viel *et al.* [1] seeking to constrain properties of warm dark matter particles. Compared to the previous work we consider a wider range on thermal histories of the intergalactic medium and find that both warm and cold dark matter models can explain the cut-off observed in the flux power spectra of high-resolution observations equally well. This implies, however, very different thermal histories and underlying re-ionisation models. We discuss how to remove this degeneracy.

Introduction. Dark matter is a central ingredient of our cosmological model. It drives the formation of structures, and explains masses of galaxies and galaxy clusters. If dark matter is made of particles, these yet-unseen particles should have been created in the early Universe long before the recombination epoch. If such particles were relativistic at early times, they would stream out from overdense regions, smoothing out primordial density fluctuations. The signature of such *warm dark matter* (WDM) scenario would be the suppression of the matter power spectrum at scales below their free-streaming horizon. From cosmological data at large scales (CMB and galaxy surveys) we know that such a suppression should be searched at comoving scales well below a Mpc.

The Lyman- α forest has been used for measuring the matter power spectrum at such scales [2–4]. While in previous works no cut-off in the transmitted flux power spectrum had been reported [5–10], and only an upper limit on the free-streaming scale had been placed, recently Viel *et al.* has observed the cut-off of the flux power spectrum at scales $k \sim 0.03 \text{ s/km}$ and redshifts $z = 4.2 - 5.4$.

However, the Lyman- α forest method measures not the distribution of dark matter itself, but only the neutral hydrogen density as a proxy for the overall matter density. The process of reionization heats the hydrogen and prevents it from clustering at small scales at the redshifts in question [11]. Therefore the observed hydrogen distribution eventually stops to follow the DM distribution. Indeed, in [1] it was demonstrated that within the Λ CDM cosmology there exists a suitable thermal history of intergalactic medium (IGM) that can explain the observed cutoff. This does not mean, however, that it is this scenario that is realised in nature.

In this Letter we investigate this issue in depth. We ask whether *the cutoff in the flux power spectrum can be attributed to the suppression of small scales with warm dark matter* and what does this mean for the thermal history of IGM. To this end we re-analyze the data used in [1], using the same suite of hydrodynamical simulations of the IGM evolution with warm and cold dark matter particles.

Data and model. The data set is constituted by 25 high-resolution quasar spectra, in the redshift interval $4.48 \leq z_{\text{QSO}} \leq 6.42$. The spectra were taken with the Keck High Resolution Echelle Spectrometer (HIRES) and the Magellan Inamory Kyocera Echelle (MIKE) spectrograph on the Magellan clay telescope. The QSO spectra are divided into four redshift bins centered on : $z = 4.2, 4.6, 5.0, 5.4$. The resulting range of wave-numbers probed by this dataset is $k = 0.005 - 0.08 \text{ s/km}$.

At these redshifts, the IGM is thought to be in a highly ionized state, being photo-ionized and photo-heated by early sources. Both the WDM cosmology and the IGM temperature affect the amount of flux power spectrum at small scales by two distinct physical mechanism: the former through the suppression in the initial matter power spectrum, the latter through Jeans and Doppler broadening of the absorption lines [11–13]. The level of ionization is captured by *the effective optical depth*, τ_{eff} , that is computed from the mean flux, $\langle F \rangle$, through the relation $\langle F(z) \rangle = \exp(-\tau_{\text{eff}}(z))$. Because the IGM spans a wide range of density, in principle describing the IGM temperature may be complicated. But, assuming that the IGM is heated by photo-heating, the temperature of the IGM follows a simple power-law *temperature-density relation* [14]:

$$T(\delta) = T_0(z)(1 + \delta)^{\gamma(z)-1}. \quad (1)$$

where $\delta = \delta\rho_{\text{m}}/\bar{\rho}_{\text{m}}$ is the matter overdensity and $T_0(z)$, $\gamma(z)$ are unknown functions of redshift. Ref. [1] considered a power-law parametrization, $T_0(z)$ and $\gamma(z)$, but let the effective optical depth vary independently in each redshift bin, $\tau_{\text{eff}}[z_i]$. In fact, from direct measurement of τ_{eff} [1] it is apparent that a single power-law in redshift is not a good description of $\tau_{\text{eff}}(z)$ at this redshift range. In this letter we have changed the priors on the IGM thermal history. We let the parameters of IGM thermal state vary independently in each redshift bin, with a total of 8 parameters describing the IGM thermal state ($T_0(z_i)$ and $\gamma(z_i)$ in 4 distinct redshift intervals). The results depend

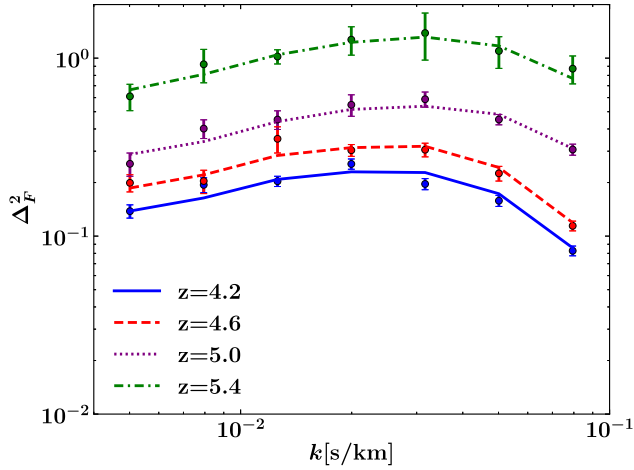


FIG. 1. Measured flux power spectrum in dimensionless units, $\Delta_F^2(k) = P_F(k) \times k/\pi$ and the theoretical model with the mean values of the astrophysical and cosmological parameters, as quoted in Table I.

also on the cosmological parameters n_s , Ω_M , σ_8 , H_0 . In the computation of the final likelihood function, Gaussian priors were applied to these parameters in order to mimic Planck constraints [15].

Results. In Table I we give the result of the parameter estimation. Figure 1 shows the theoretical flux power spectrum for the mean values of the parameters, compared with the MIKE and HIRES data used in this analysis. In Fig. 2 we show the 2D confidence regions between m_{WDM} , and $T_0 \equiv T(\delta=0)$ (marginalizing over the other parameters). We see that at redshifts $z = 4.2, 4.6$ there is no degeneracy and the IGM temperature $T_0 \sim 10^4$ K is needed to explain the observed flux power spectrum independently of m_{WDM} . If dark matter is “too warm” ($m_{\text{WDM}} < 1.5$ keV) it produces too sharp of a cut-off in the power spectrum and is inconsistent with the data.

At $z = 5.0$ bin the situation is different. For the masses $m_{\text{WDM}} \sim 2.2 - 3.3$ keV even very low temperatures $T_0 \lesssim 2500$ K are consistent with the data. In this case the cutoff in the flux power spectrum is explained by WDM rather than by the temperature. The situation is analogous at $z = 5.4$. Table I summarizes the parameter estimation.

Another important property of Fig. 2 is that even assuming CDM cosmology, temperature T_0 is a non-monotonic function of redshift and should be colder than ~ 8000 K at $z = 5.0 - 5.4$, see Fig. 3.¹

¹ The temperature values that we have estimated at high redshift could be inaccurate, because the lowest temperature in the simulation grid was 5400 K.

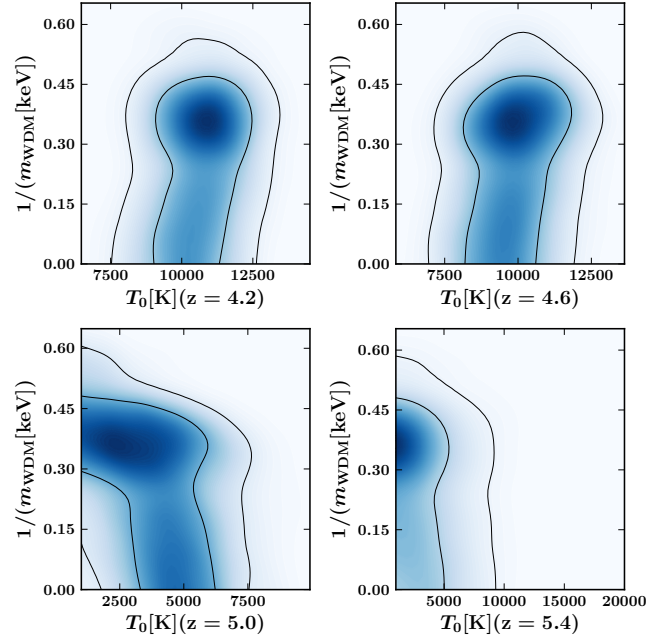


FIG. 2. Confidence regions between the WDM mass, m_{WDM} , and the IGM mean temperature, T_0 , at all redshift.

We would like to stress that all these results depend crucially on allowing for non-monotonic redshift dependence of $T_0(z)$. In [1] it was shown that assuming a power-law (*monotonic*) redshift dependence for $T_0(z)$ and $\gamma(z)$, one predicts higher temperatures of IGM for the same data. In this case the CDM cosmology is preferred over WDM, leading to the 2σ lower bound $m_{\text{WDM}} \geq 3.3$ keV [1], while our assumptions allow to relax this bound down to $m_{\text{WDM}} \geq 2.1$ keV. Moreover, the non-monotonic thermal history makes WDM with $m_{\text{WDM}} = 2 - 3$ keV equally good fit as CDM (see Fig. 4)

For the interpretation of these results it is crucial to overview what is known about the thermal state of the IGM both theoretically and observationally. We argue below that the measured thermal history is in agreement with current models of galaxy formation and reionization.

State of the IGM at $z \sim 5$. The IGM temperature can be *determined* from the broadening of the Lyman- α absorption lines in QSO spectra [13, 16–26]. Alternatively, it has been proposed to determine the IGM temperature by measuring the level of the transmitted flux [25, 27–29], however there is no agreement between two methods yet, see [30].

The IGM temperatures at $z < 5$ is constrained relatively well to be at the level $T_0 \gtrsim (8 - 10) \times 10^3$ K [17, 20, 22, 23]. At $z = 6.0$ there is a single measurement, [24], that restricts T_0 to the range $5000 < T_0 < 10000$ K (68% CL) (see e.g. [1] for discussion). The simplest interpretation of these data (adopted also in [1]) is that

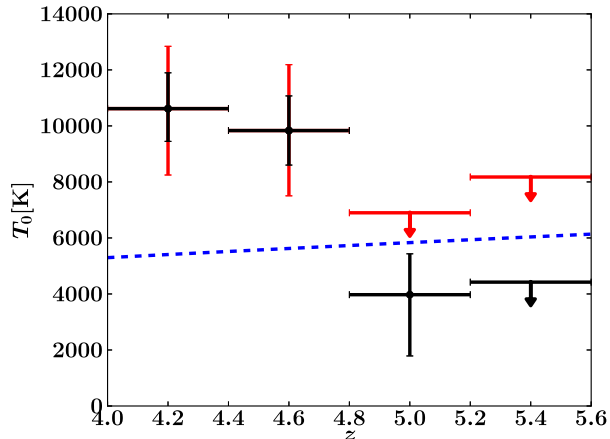


FIG. 3. The evolution of the IGM mean temperature, T_0 , in redshift. Black vertical bars are $1\text{-}\sigma$ confidence limits; red vertical bars are $2\text{-}\sigma$ confidence limits. Filled dots are the parameter mean; the arrows mark the upper limits. The horizontal bars span the redshift interval of Lyman α absorbers considered for each measurement of the flux power spectrum. For the redshift intervals centered on $z = 5.0$ there is a $1\text{-}\sigma$ level detection and only an upper limit at $2\text{-}\sigma$ level. For $z = 5.4$ there are only upper limits at $1\text{-}\sigma$ and $2\text{-}\sigma$ levels. The blue dashed line is the asymptotic IGM mean temperature in the case of early hydrogen and first helium reionization from a stellar ionizing spectrum with slope $\alpha = 2$, being the ionizing spectrum $J_\nu \propto \nu^{-\alpha}$.

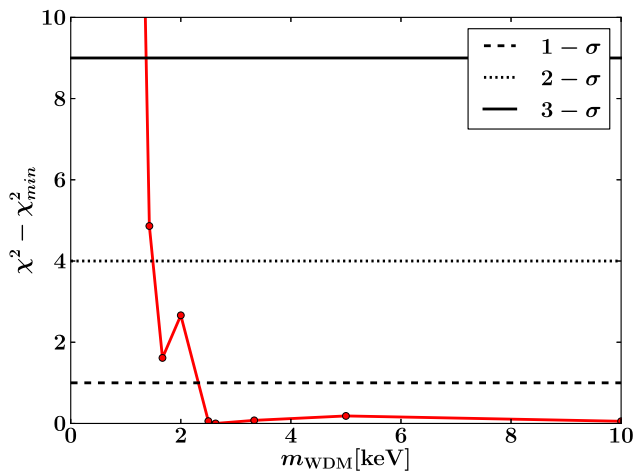


FIG. 4. The results of the frequentist analysis: the $\chi^2 - \chi^2_{min}$ versus the WDM mass, m_{WDM} .

the temperature is growing monotonically with redshift. Instead, given the large error bars of the measurements and taking into account the adiabatic cooling one may expect a drop of temperature at $z \sim 5$ with a subsequent rise to $\sim 10^4$ K at $z \sim 4.6$ in agreement with other measurements from [17, 20, 22, 23]. This increase in IGM temperature can be explained with an early start

TABLE I. Parameter estimation from Bayesian analysis. We show the $1\text{-}\sigma$ and $2\text{-}\sigma$ confidence intervals.

parameter	mean	$1\text{-}\sigma$	$2\text{-}\sigma$
$H_0[\text{km/s/Mpc}]$	63	< 67	–
$1/(m_{\text{WDM}}[\text{keV}])$	0.26	[0.007, 0.44]	< 0.47
$T_0(z = 4.2)[10^3 \text{ K}]$	10.6	[9.4, 11.8]	[8.3, 12.9]
$T_0(z = 4.6)[10^3 \text{ K}]$	9.8	[8.6, 11.1]	[7.5, 12.2]
$T_0(z = 5.0)[10^3 \text{ K}]$	4.0	[2.0, 5.6]	< 6.9
$T_0(z = 5.4)[10^3 \text{ K}]$	3.8	< 4.5	< 8.2
$\tau_{\text{eff}}(z = 4.2)$	1.12	[1.05, 1.19]	[1.00, 1.25]
$\tau_{\text{eff}}(z = 4.6)$	1.30	[1.21, 1.39]	[1.15, 1.47]
$\tau_{\text{eff}}(z = 5.0)$	1.88	[1.74, 2.00]	[1.64, 2.13]
$\tau_{\text{eff}}(z = 5.4)$	2.91	[2.69, 3.10]	[2.54, 3.31]
$\gamma(z = 4.2)$	1.3	> 1.1	–
$\gamma(z = 5.4)$	1.3	> 1.1	–

of HeII reionization predicted for some models of reionization by quasars, [31] (see recent discussion of such “two-component” reionization models in [32]).

In such a scenario, the temperature at $5 < z < 6$ depends on how long the first stage of reionization had lasted and what was the temperature of IGM at $z \gtrsim 6$. As mentioned above, the measurement [24] at $z \sim 6$ has large uncertainties. Theoretically $T_0(z=6)$ depends on how early the first stage of hydrogen (and HeI) reionizations has ended, and what sources were driving it (c.f. [33, 34]). It has been speculated that hydrogen is reionized by the metal-free (Population III) stars, whose hardness of the spectra predicts high values of the temperature. However, the properties of Population III stars are purely speculative – we do not know how long they lasted and whether they were indeed the sources of reionization. For example, reionization could be due to a more metal enriched population of stars with a softer stellar spectra [35], leading to a lower values of IGM temperature at $z \sim 6$. To settle this question, an independent constraint on the ultraviolet background at high redshift would be needed, however there are no such measurements to-date. The lower limit of Bolton *et al.* [24] is $T_0(z=6) \approx 5 \times 10^3$ K or even slightly below, fully consistent with the low values at $z = 5.0 - 5.4$ (Table I) reached via adiabatic cooling.

Finally, we note that an indirect argument in favour of the IGM temperatures at high redshifts being $\sim 10^4$ K, is the “missing satellite problem” – high temperature would prevent gas from collapsing into dark matter halos with the mass below $\sim 10^7 M_\odot$, thus suppressing the formation of small galaxies (see e.g. [36–39]), explaining in particular the small number of satellites of the Milky Way (the so-called *missing satellite problem*). However, in the WDM cosmologies the matter power spectrum is suppressed at the smallest scales, thus solving the missing satellite problem even if the gas was sufficiently cooler.

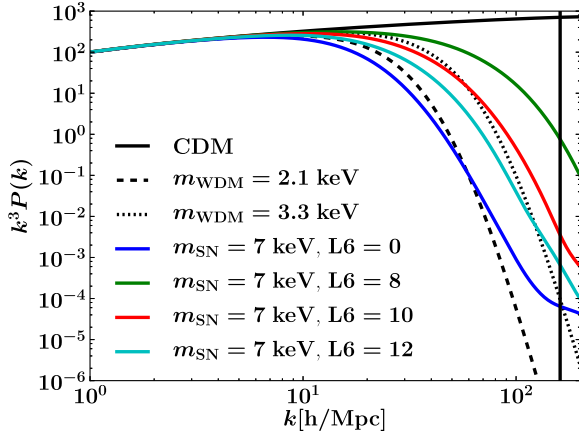


FIG. 5. Comparison between matter power spectra from CDM, WDM thermal relic and SNs. The solid black line is the matter power spectrum for CDM, the dashed (dotted) black line is the matter power spectrum for $m_{\text{WDM}} = 2.1$ keV ($m_{\text{WDM}} = 3.3$ keV) as computed in [10]. The colored (green, red, cyan) lines are realistic matter power spectra for some of the sterile neutrino models with $m_{\text{SN}}^{\text{NRP}} = 7$ keV. The matter power spectra with $L_6 = 10$ and 12 (red and cyan lines) are partially warmer than the lower bound of [1] (the dotted black line), but still satisfy the constraints from this letter (the dashed black line) until the maximum k -mode used in the reference numerical simulations. The matter power spectrum with $L_6 = 8$ (green line) is colder than the bound of [1]. The matter power spectra with $L_6 = 0$ (blue line) violates the constraint from this letter. The solid vertical line is the maximum k -mode used in the reference simulations.

Conclusion and future work. We demonstrated that cut-off in the flux power spectrum, observed in the high resolution Lyman- α forest data may either be due to free-streaming of dark matter particles or be explained by the temperature of the intergalactic medium. Taking into account measurements at redshifts $z \sim 6$ and at $z < 5$ we see that if dark matter is *warm* – this requires non-monotonic dependence on the IGM temperature on z with the local minimum at $z \sim 5.0 - 5.4$. Even cold dark matter slightly prefers a non-monotononic $T_0(z)$.² Improving our knowledge of the IGM temperature at $z \sim 5 - 6$ will therefore either result in very strong Lyman- α bounds on DM free-streaming, essentially excluding its influence on observable small-scale structures, or (if temperature will be found to be well below 5000 K) would lead to the discovery of WDM.

² As stated in [40], a model of fluctuating UVB, with spatially constant mean free path for the hydrogen-ionizing photons (similar to the one used in [1] and in this work) may not be adequate to explain the observed scatter in the optical depth at redshifts $5.1 \leq z \leq 5.7$. Proper modeling of patchy reionization may affect the conclusions about the IGM state. We leave this for future work.

A method that would allow to measure the IGM temperature at redshifts of interest was presented in [13]. It is based on the following idea: for high resolution spectra it is not necessary to study average deviation from QSO continuum per redshift bins (as it is done in lower resolution case) but it is possible to identify individual absorption lines and to measure their broadening. The thermal Doppler effect broadens the natural lorentzian line profile of the Lyman α transition proportionally to the square root of the temperature, and one would like to use this information to determine *directly* the temperature of the IGM. However, there are other effects that contributes to the line width – physical extent of the underlying filaments and the clustering of the underlying filaments. The method of [13] allows to disentangle these effects. In view of our results it is important to attempt to apply this method to the data in question.

Finally, we use our results to explore the constraints on non-thermal warm dark matter – sterile neutrino, resonantly produced in the presence of lepton asymmetry [41–43]. Primordial phase-space density distribution of these particles resembles a mixture of cold+warm dark matter components [44, 45], demonstrating shallower cut-off. We compare the linear power spectra of allowed thermal relic WDM ($m_{\text{WDM}} = 2.1$ keV) and those of resonantly produced sterile neutrinos with the mass 7 keV (motivated by the recent reports of an unidentified spectral line at the energy $E \sim 3.5$ keV in the stacked X-ray spectra of Andromeda galaxy, Perseus galaxy clusters, stacked galaxy clusters and the Galactic Center of the Milky Way [46–48]). We show that depending on the value of lepton asymmetry, $L_6 \equiv 10^6(n_{\nu_e} - n_{\bar{\nu}_e})/s$ (see [45] for details) the linear power can be colder than those of thermal relics with $m_{\text{WDM}} = 2.1$ keV (Fig. 5), thus being fully admissible by the data.³ Notice that the non-resonant sterile neutrino dark matter with 7 keV mass would be excluded at more than 3σ level by previous constraints from the SDSS [6, 7].

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³ Our computations of the phase-space distribution functions for sterile neutrinos are based on [43] and the linear power spectrum is obtained with the modified CAMB code developed in [44]. We do not expect the most recent computations [49, 50] to affect our results.

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- [1] M. Viel, G. D. Becker, J. S. Bolton, and M. G. Haehnelt, *Phys. Rev. D* **88**, 043502 (2013), [arXiv:1306.2314 \[astro-ph.CO\]](#).
- [2] R. A. C. Croft, D. H. Weinberg, N. Katz, and L. Hernquist, *Astrophys. J.* **495**, 44 (1998), [arXiv:astro-ph/9708018 \[astro-ph\]](#).
- [3] P. McDonald, J. Miralda-Escude, M. Rauch, W. L. W. Sargent, T. A. Barlow, R. Cen, and J. P. Ostriker, *Astrophys. J.* **543**, 1 (2000), [arXiv:astro-ph/9911196 \[astro-ph\]](#).
- [4] R. A. C. Croft, D. H. Weinberg, M. Bolte, S. Burles, L. Hernquist, N. Katz, D. Kirkman, and D. Tytler, *Astrophys. J.* **581**, 20 (2002), [arXiv:astro-ph/0012324 \[astro-ph\]](#).
- [5] S. H. Hansen, J. Lesgourgues, S. Pastor, and J. Silk, *Mon. Not. Roy. Astron. Soc.* **333**, 544 (2002), [arXiv:astro-ph/0106108 \[astro-ph\]](#).
- [6] A. Boyarsky, J. Lesgourgues, O. Ruchayskiy, and M. Viel, *JCAP* **0905**, 012 (2009), [arXiv:0812.0010 \[astro-ph\]](#).
- [7] U. Seljak, A. Makarov, P. McDonald, and H. Trac, *Phys. Rev. Lett.* **97**, 191303 (2006), [arXiv:astro-ph/0602430 \[astro-ph\]](#).
- [8] M. Viel, G. D. Becker, J. S. Bolton, M. G. Haehnelt, M. Rauch, and W. L. W. Sargent, *Phys. Rev. Lett.* **100**, 041304 (2008), [arXiv:0709.0131 \[astro-ph\]](#).
- [9] M. Viel, J. Lesgourgues, M. G. Haehnelt, S. Matarrese, and A. Riotto, *Phys. Rev. Lett.* **97**, 071301 (2006), [arXiv:astro-ph/0605706 \[astro-ph\]](#).
- [10] M. Viel, J. Lesgourgues, M. G. Haehnelt, S. Matarrese, and A. Riotto, *Phys. Rev. D* **71**, 063534 (2005), [arXiv:astro-ph/0501562 \[astro-ph\]](#).
- [11] N. Y. Gnedin and L. Hui, *Mon. Not. Roy. Astron. Soc.* **296**, 44 (1998).
- [12] T. Theuns, J. Schaye, and M. G. Haehnelt, *MNRAS* **315**, 600 (2000).
- [13] A. Garzilli, T. Theuns, and J. Schaye, *Mon. Not. Roy. Astron. Soc.* **450**, 1465 (2015), [arXiv:1502.05715 \[astro-ph.CO\]](#).
- [14] L. Hui and N. Y. Gnedin, *Mon. Not. Roy. Astron. Soc.* **292**, 27 (1997), [arXiv:astro-ph/9612232 \[astro-ph\]](#).
- [15] Planck Collaboration, P. A. R. Ade, N. Aghanim, M. I. R. Alves, C. Armitage-Caplan, M. Arnaud, M. Ashdown, F. Atrio-Barandela, J. Aumont, H. Aussel, and et al., *A&A* **571**, A1 (2014).
- [16] T. Theuns and S. Zaroubi, *Mon. Not. Roy. Astron. Soc.* **317**, 989 (2000), [arXiv:astro-ph/0002172 \[astro-ph\]](#).
- [17] P. McDonald, J. Miralda-Escude, M. Rauch, W. L. W. Sargent, T. A. Barlow, and R. Cen, *Astrophys. J.* **562**, 52 (2001), [Erratum: *Astrophys. J.* 598, 712 (2003)], [arXiv:astro-ph/0005553 \[astro-ph\]](#).
- [18] M. Zaldarriaga, L. Hui, and M. Tegmark, *Astrophys. J.* **557**, 519 (2001), [arXiv:astro-ph/0011559 \[astro-ph\]](#).
- [19] M. Viel and M. G. Haehnelt, *Mon. Not. Roy. Astron. Soc.* **365**, 231 (2006), [arXiv:astro-ph/0508177 \[astro-ph\]](#).
- [20] J. Schaye, T. Theuns, M. Rauch, G. Efstathiou, and W. L. W. Sargent, *Mon. Not. Roy. Astron. Soc.* **318**, 817 (2000), [arXiv:astro-ph/9912432 \[astro-ph\]](#).
- [21] M. Ricotti, N. Y. Gnedin, and J. M. Shull, *Astrophys. J.* **534**, 41 (2000), [arXiv:astro-ph/9906413 \[astro-ph\]](#).
- [22] A. Lidz, C. A. Faucher-Giguere, A. Dall’Aglio, M. McQuinn, C. Fechner, M. Zaldarriaga, L. Hernquist, and S. Dutta, *Astrophys. J.* **718**, 199 (2010), [arXiv:0909.5210 \[astro-ph.CO\]](#).
- [23] G. D. Becker, J. S. Bolton, M. G. Haehnelt, and W. L. W. Sargent, *Mon. Not. Roy. Astron. Soc.* **410**, 1096 (2011), [arXiv:1008.2622 \[astro-ph.CO\]](#).
- [24] J. S. Bolton, G. D. Becker, S. Raskutti, J. S. B. Wyithe, M. G. Haehnelt, and W. L. W. Sargent, *MNRAS* **419**, 2880 (2012).
- [25] A. Garzilli, J. S. Bolton, T. S. Kim, S. Leach, and M. Viel, *Mon. Not. Roy. Astron. Soc.* **424**, 1723 (2012), [arXiv:1202.3577 \[astro-ph.CO\]](#).
- [26] G. C. Rudie, C. C. Steidel, and M. Pettini, *ApJ* **757**, L30 (2012), [arXiv:1209.0005 \[astro-ph.CO\]](#).
- [27] J. S. Bolton, M. Viel, T. S. Kim, M. G. Haehnelt, and R. F. Carswell, *Mon. Not. Roy. Astron. Soc.* **386**, 1131 (2008), [arXiv:0711.2064 \[astro-ph\]](#).
- [28] M. Viel, J. S. Bolton, and M. G. Haehnelt, *Mon. Not. Roy. Astron. Soc.* **399**, L39 (2009), [arXiv:0907.2927 \[astro-ph.CO\]](#).
- [29] F. Calura, E. Tescari, V. D’Odorico, M. Viel, S. Cristiani, T. S. Kim, and J. S. Bolton, *Mon. Not. Roy. Astron. Soc.* **422**, 3019 (2012), [arXiv:1201.5121 \[astro-ph.CO\]](#).
- [30] E. Rollinde, T. Theuns, J. Schaye, I. Pâris, and P. Petitjean, *MNRAS* **428**, 540 (2013).
- [31] M. McQuinn, A. Lidz, M. Zaldarriaga, L. Hernquist, P. F. Hopkins, S. Dutta, and C.-A. Faucher-Giguere, *ApJ* **694**, 842 (2009).
- [32] P. Madau and F. Haardt, (2015), [arXiv:1507.07678 \[astro-ph.CO\]](#).
- [33] F. Haardt and P. Madau, *ApJ* **461**, 20 (1996).
- [34] L. Hui and Z. Haiman, *ApJ* **596**, 9 (2003).
- [35] B. Ciardi and A. Ferrara, *Space Sci. Rev.* **116**, 625 (2005).
- [36] A. J. Benson, C. G. Lacey, C. M. Baugh, S. Cole, and C. S. Frenk, *Mon. Not. Roy. Astron. Soc.* **333**, 156 (2002), [arXiv:astro-ph/0108217 \[astro-ph\]](#).
- [37] A. J. Benson, C. S. Frenk, C. G. Lacey, C. M. Baugh, and S. Cole, *Mon. Not. Roy. Astron. Soc.* **333**, 177 (2002), [arXiv:astro-ph/0108218 \[astro-ph\]](#).
- [38] A. V. Maccio’, X. Kang, F. Fontanot, R. S. Somerville, S. E. Koposov, et al., *MNRAS* **402**, 1995 (2009).
- [39] T. Sawala, C. S. Frenk, A. Fattahi, J. F. Navarro, R. G. Bower, R. A. Crain, C. Dalla Vecchia, M. Furlong, A. Jenkins, I. G. McCarthy, Y. Qu, M. Schaller, J. Schaye, and T. Theuns, *ArXiv e-prints* (2014).
- [40] G. D. Becker, J. S. Bolton, P. Madau, M. Pettini, E. V. Ryan-Weber, and B. P. Venemans, *Mon. Not. Roy. Astron. Soc.* **447**, 3402 (2015), [arXiv:1407.4850 \[astro-ph.CO\]](#).
- [41] X.-D. Shi and G. M. Fuller, *Phys. Rev. Lett.* **82**, 2832 (1999), [arXiv:astro-ph/9810076 \[astro-ph\]](#).
- [42] K. Abazajian, G. M. Fuller, and M. Patel, *Phys. Rev. D* **64**, 023501 (2001).
- [43] M. Laine and M. Shaposhnikov, *JCAP* **0806**, 031 (2008), [arXiv:0804.4543 \[hep-ph\]](#).
- [44] A. Boyarsky, J. Lesgourgues, O. Ruchayskiy, and M. Viel, *Phys. Rev. Lett.* **102**, 201304 (2009), [arXiv:0812.3256 \[hep-ph\]](#).
- [45] A. Boyarsky, O. Ruchayskiy, and M. Shaposhnikov, *Ann. Rev. Nucl. Part. Sci.* **59**, 191 (2009), [arXiv:0901.0011 \[hep-ph\]](#).
- [46] E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein, and S. W. Randall, *Astrophys. J.* **789**,

- 13 (2014), [arXiv:1402.2301 \[astro-ph.CO\]](#).
- [47] A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi, and J. Franse, *Phys. Rev. Lett.* **113**, 251301 (2014), [arXiv:1402.4119 \[astro-ph.CO\]](#).
- [48] A. Boyarsky, J. Franse, D. Iakubovskyi, and O. Ruchayskiy, *Phys. Rev. Lett.* **115**, 161301 (2015), [arXiv:1408.2503 \[astro-ph.CO\]](#).
- [49] J. Ghiglieri and M. Laine, (2015), [arXiv:1506.06752 \[hep-ph\]](#).
- [50] T. Venumadhav, F.-Y. Cyr-Racine, K. N. Abazajian, and C. M. Hirata, (2015), [arXiv:1507.06655 \[astro-ph.CO\]](#).